THE DIFFERENTIAL ACTION OF CERTAIN MUSCLES PASSING MORE THAN ONE JOINT.

BY THOMAS EAKINS.

It is not without diffidence, that I, a painter, venture to communicate with a scientific body upon a scientific subject; yet I am encouraged by thinking that Nature is so many sided that the humblest observer may, from his point of view, offer suggestions worthy of attention. I am greatly indebted to Dr. Harrison Allen, who has kindly added some explanatory notes.

I have long been dissatisfied with the account in standard works of the muscular action in animal locomotion. The muscles are classified principally as flexors and extensors, working and resting alternately. Wishing to apply this system during my early dissections to the leg of the living horse, I was surprised to observe in the strain of starting a horse car, that the so-called flexors and extensors were in strong action at the same time.

The classification was still farther from satisfactory when applied to muscles passing over two or more joints, flexing perhaps one joint, while extending another. In trying to understand the significance of these last named muscles, I came to believe it to be very important to discover if the one joint was extended more rapidly than the other was flexed. This investigation demanded a consideration of the amount and kind of leverage, and was extended from the muscles to tendons [1] which pass over the two or more joints. I next constructed a model of the entire limb with flat pieces of half-inch pine board, cut to the outline of the bones, the pieces pivoted together, having catgut for tendons and ligaments, and rubber bands for muscles, all attached to their places and properly restrained.

I had then the satisfaction of seeing this mechanism imitate in many ways the action of the real leg, and was enabled to establish two important principles, thus: First, the hoof-pieces properly set upon the ground, the leg stood firm, all tendency to collapse being prevented by the leverage of tendons passing joints. Secondly, the

[1] The use of the word "tendons" in the sense here employed, does not refer to the tendons in connection with muscular bellies, but to ligament-like structures which are homologous with the muscles as these bodies are uniformly assigned by authors to the musculature of the limbs. H. Allen.

tightening of the rubber bands representing all the principal muscles, both the so-called flexors and the so-called extensors, *at the same time*, caused the upper part of the limb to spring forward when released, and proved to me that I was not mistaken in my observation on the living horse.

Returning to the dead horse, I denuded both a front and back leg of every shred of muscular fibre, yet they sustained weight.

There was no tendency to collapse, and an increase in the weight only measured an increase of resistance.[2] (If one wishes to repeat my experiment with the dead horse and should choose the front leg, he must respect the large tendon concealed in the biceps brachialis which might escape a careless dissection, especially by one accustomed rather to dissections of the human body.) Observation of the living horse will teach us, that, if he wishes to lie down, he must first flex the pastern, and the stumbling horse must strike the hoof with force enough to flex the phalanges before he can go down.

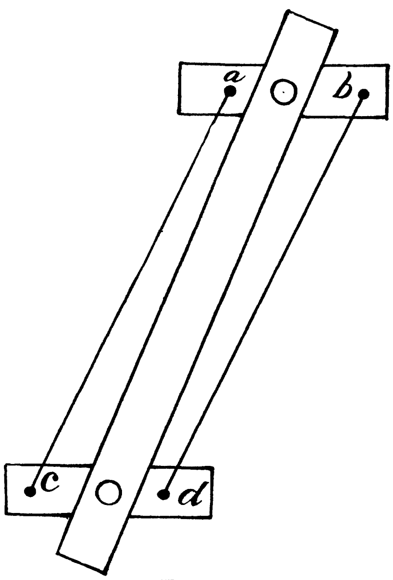

FIG. 1.

To illustrate in the *simplest* way the scheme of the muscles and tendons passing more than one joint I pivoted one little flat stick upon two others (fig. 1), and on the horizontal sticks I drove in four pins leaving the heads project slightly, the pin *a* close to the upper joint, the pin *b* farther from it; the pin *d* close to the lower joint, the pin *c* farther. If two inextensible strings be looped, one from *a* to *c*, the other from *b* to *d*, the upper horizontal piece is held up and will sustain weight. The

[2] Mr. Eakins exhibited to the members of the Academy photographs made by him at the University of Pennsylvania in 1883, showing the front and back leg of a dissected horse, all the muscles having been removed. Nevertheless the limbs sustained weight. H. Allen.

a end cannot go down on account of the string *b d* and the *b* end cannot go down for the string *a c*. If rubber bands be stretched on the same pins, then the upper horizontal piece will, if released, spring forward very far and very fast compared with the actual shortening of the rubbers (fig. 2).

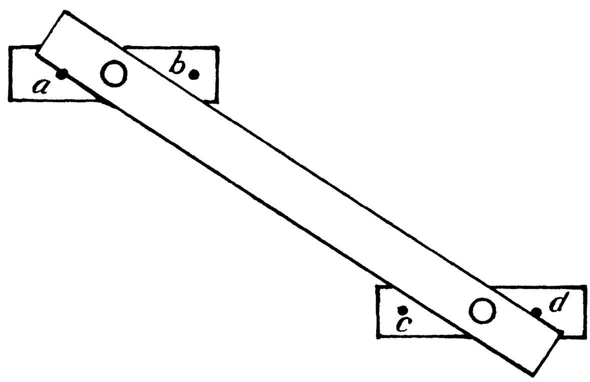

FIG. 2.

The model of the entire limb had all the merit of a first approximation. It imitated pretty closely the movement of the leg itself. A second and closer approximation can now be had by considering in terms of my first elements, the variations from Nature made in them to gain simplicity of construction. In the first place, articular surfaces are not circular, so that a pivot does not accurately represent their motion. Neither do bones moving in constraint, one against the other, keep in the same plane, but their axes describe warped surfaces from the helical character of the articulations.

There is a constant change in the relative rates of motion of the joints, involving likewise a constant change in the relative leverage.

The problem becomes instantly one of extreme difficulty, yet a fair appreciation may be obtained.

The leg should be studied in several positions not consecutive, but so far apart as to cause decided changes in the relative rates of the different levers, and so small a part of the path or trajectory should be considered, that a simple curve or straight line may, without error, be substituted as in the manner of studying evolutes.

I now draw the bones of the front leg of the horse (fig. 3), and of the hind leg (fig. 4), and with heavy black lines represent those

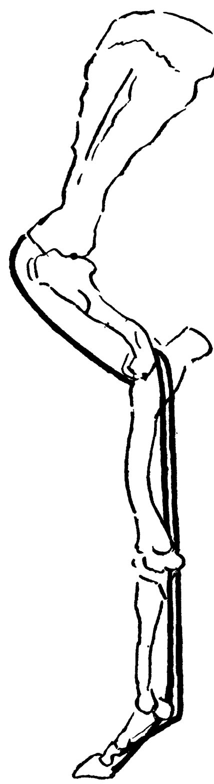

FIG. 3.

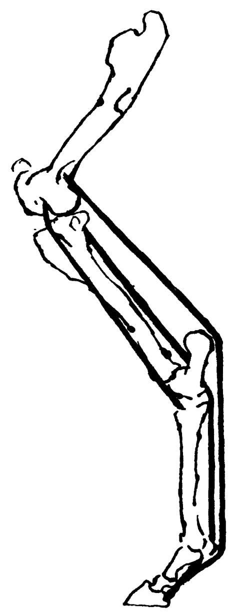

FIG. 4.

tendons which suffice to hold up the entire weight of the horse, and which, by their leverage in conjunction with the shapes of the articular surfaces of the joints, determine the trajectory of the horse's movement. (It seems likely that in the long run it was the trajectory which determined the length and position of the tendons and the shapes of the surfaces.)

In the diagram of the front leg I would like to call attention to the humerus having its upper joint, the one with the scapula, well back; while its lower joint, with the radius, lies well forward. The

great tendon running through the front part of the biceps brachialis has a very short leverage below and a long one above.[3]

In the hind leg you will notice that the femora-tibial joint is well back, while the astragalo-tibial joint is well forward, and the tendon in front of the tibia takes a longer leverage above than below, with this condition reversed in the two tendons behind the tibia.

When a horse stands in his usual position, the tendons which I have drawn sustain his weight in stable equilibrium, because his centre of gravity is at the lowest point of its trajectory.

The upper end of the dissected leg weighted heavily and moved backward and forward in the vicinity of the standing position, will there describe as a trajectory a flattish curve with its concavity upwards. At the lowest point of this concavity the leg settles when the horse ceases his muscular effort and simply stands. Any muscular effort that the horse may make from the standing position begins by raising himself. (A horse may, and often does, especially in haunching himself, maintain his weight at a still higher point behind by raising himself and slipping his patella over the inner trochlear surface of the femur, where it locks itself, and the weight of the trunk is again sustained without muscular effort. To unlock the patella traction is made by the tensor vaginæ femoris).

To investigate the action of a muscle I believe it necessary to consider it, not only with reference to the levers to which it is attached, but with relation to the whole movement of the animal. Then it will be seen that many muscles rated in the books as antagonistic, are no more so than are two parts of the same muscle. As an example, let us take the gastrocnemius. It is a short muscle, and takes its origin above the knee, and is inserted by means of a long tendon (the tendo Achillis) into the calcaneum. It is said in standard anatomies of the horse to be a flexor of the knee joint, of the leg on the thigh, and also to be an extensor of the ankle joint. As a flexor of the knee joint the muscle would be antagonistic to the great triceps

[3] The anatomist would express these facts as follows:

The distal end of the scapula and the proximal end of the humerus are not all engaged in the formation of the shoulder-joint. The joint, indeed, lies well back and constitutes less than one-third of the relatively enormous area. I wish particularly to have noted, that the contact between the surfaces in the joint takes place as shown in figure 3, near the re-entering posteriorly placed angle, which is formed between the scapula and the humerus, while, as opposed to this, the contact at the elbow joint between the distal end of the humerus and the proximal end of the radius takes place well forward, so as to be near the re-entering anteriorly placed angle between these two bones. H. Allen.

extensor of the thigh. The great extensor cruris, however, pulling on the knee-cap and straightening the knee joint, continually moves forward the origin of the gastrocnemius muscle, and the latter pulling on the calcaneum and contracting itself at the same time, draws forward the calcaneum faster than the origin moves forward and acts during the whole step. The muscular fibres of the gastrocnemius are so short in the horse, that if the origin were not moved forward, this muscle would reach its limit of contraction long before the end of the step. Thus then, the gastrocnemius is auxiliary to the triceps, not antagonistic.

To prove this completely, let us cut away in the dissected horse the triceps and every other muscle except the gastrocnemius, which we will contract. Its action is precisely as before. It draws forward the calcaneum, but it *extends*, not *flexes* the knee.

The paradox disappears when we study a tendon running up the other side of the tibia, the tendinous portion of the flexor metatarsi. This tendon takes a greater leverage (fig. 5) on the upper or knee joint that it passes, than on the lower or ankle joint, that it also passes; but the muscle has the reverse leverage. It takes a shorter leverage at the knee than at the ankle. In contracting, therefore, it raises the calcaneum, drawing down the flexor metatarsi tendon as shown by the direction of the arrow in the drawing, and the flexor metatarsi extends the knee-joint. Understanding then the differential action of the gastrocnemius muscle, we might look upon the triceps as the auxiliary of the gastrocnemius in extending the knee-joint.

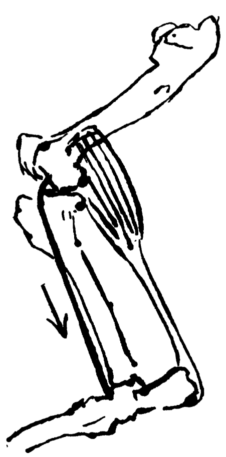

FIG. 5.

The great muscles of the posterior aspect of the thigh, the long vast of the veterinarians (part of glut. max.), the biceps, the semi-tendinosus, the semi-membranosus, the gracilis, are inserted not above the knee but below it; not to flex the knee in progression, but to draw on an insertion that in a differential manner is moving away from the origin of the muscles, in order that the whole of the contractions may be utilized in the whole stride. In progression, then, the croup muscles are auxili-

aries to the great triceps on the other side of the femur and to the gastrocnemius.

The arrangement and action of the thigh muscles are imitated by the rubber bands of the small model (fig. 1). The up and down stick represents the femur, the upper horizontal stick the pelvis, the lower stick the upper end of the tibia. The rubber band from *a* to *c* is the rectus femoris muscle, with a short leverage above and a long one below. The rubber band from *b* to *d* is one of the croup muscles with a greater leverage above than below. The simultaneous shortening of the muscles on both sides of the femur throws, then, the pelvis forward *far* and *fast* compared with the actual contraction in the lines of the muscles themselves.

To show how little this differential co-ordinate action of the muscles and tendons has been understood, I shall quote a passage from Chauveau.[4]

Speaking of the tendinous portion of the flexor metatarsi he says:

"Some have attributed to it still another use, that of passively opposing itself to the flexion of the femur on the leg while standing, and serving thus as an auxiliary to the muscular forces which hold in equilibrium the weight of the body. This is wrong according to us. For it to fulfil this function, the foot would have to be held in a fixed situation by the contraction of its extensor muscles. Now these muscles are indeed the gastrocnemii of the leg, which take their origin behind the femur, and which tend to flex this bone on the tibia, that is to say, to cause the movement which they are supposed to be charged to hinder."

" Besides, experiment shows pretty well that we are right ; the cutting of this tendinous cord, practised on the living animal, does not change its appearance while resting on one or both hind legs."

[4] "Ce tendon jouit de la curieuse propriété de plier le jarret par une action toute mécanique, lors de la flexion des rayons supérieurs du membre. On lui a encore attribué un autre usage, celui de s' opposer passivement à la flexion du fémur sur la jambe pendant la station et de servir ainsi d' adjuvant aux forces musculaires qui font équilibre au poids du corps. C'est à tort, suivant nous. Pour qu' elle (corde conductrice) pût remplir ce rôle, il faudrait que le pied fût maintenu en situation fixe par la contraction de ses muscles extenseurs. Or, ces muscles sont justement les jumeaux de la jambe, qui prennent leur origine en arrière du fémur et qui tendent à opérer la flexion de cet os sur le tibia, c'est-à-dire à déterminer le mouvement qu' on les suppose chargés d' empêcher. L' experimentation, du reste, montre assez que nous sommes dans le vrai: la section de cette corde tendineuse, pratiquée sur l' animal vivant, ne trouble nullement l'habitude extérieure de celui-ci, ni pendant la station libre, ni pendant la station forcée." Chauveau. Traité d'Anatomie Comparée des Animaux domestiques. Page 357.

Now these people are right in attributing to the flexor metatarsi tendon the function of opposing itself to the flexion of the femur, and wrong only in making this function auxiliary to muscular forces, which are not called upon to sustain weight, and which if called upon in the usual way would start progression.

"To fulfil the function of sustentation," says Chauveau, "the foot would have to be held by the gastrocnemii muscles which," he says, "tend to flex the femur on the tibia."

My experiment with the dead horse, the muscular fibres having been cut away, shows that the perforatus and perforans tendons maintain the foot, without the assistance of the gastrocnemius muscle, which does not flex the former upon the tibia, but *extends* it, as I have shown before. I mistrust entirely the accuracy of Chauveau's observation as to the effect of cutting the tendon in the living horse. The severance of this mighty cord in the dead horse causes instant collapse. I suspeect that in Chauveau's experiment the cord was but imperfectly cut; or, it may be, that by an extraordinary co-ordination of muscular effort the poor beast still stood for a short time previous to its final destruction, but it is inconceivable to me that a trained and unprejudiced observer should detect no change in the appearance of the animal upon the destruction of such a great part of the mechanism.

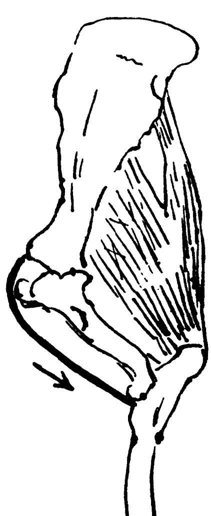

FIG. 6.

I shall close this communication with another beautiful example of muscular differential action. In the arm of the horse (fig. 6) we have two principal muscles, the biceps in front of the bone and the triceps behind. The biceps flexor radialis surrounds the tendon which I have drawn in heavy black line, and takes a long leverage above, at the shoulder joint, and a very short one below, on the radius. The long head of the triceps arises from the axillary border of the scapula, and is inserted into the olecranon. The olecranon is set far back and above the elbow joint, to afford to the triceps a greater leverage below than above, reversing the condition of the biceps. These two muscles, during the act of progression, form a complete circuit of strain. The action of the

biceps is to extend the scapula on the humerus. This extension of the scapula pulls through the triceps on the olecranon, and thus gives the biceps a longer leverage on the radius than its own tendon gives it in front of the elbow joint. Consequently the biceps extending the scapula also extends, not flexes, the radius.

The long head of the triceps, with its long leverage on the olecranon, extends the forearm, but in so doing it pulls on the tendon of the biceps which, with its short leverage below and long leverage above, extends the shoulder joint, notwithstanding the direct insertion of the triceps into the scapula. The simultaneous contraction of the two muscles will raise the shoulder-blade above the tendinous trajectory, in replacing the tendons and aponeuroses by shorter lines. This causes, especially towards the end of the stride, the great difference between the trajectories of the dead and the living horse. Other circuits of strains connect this part of the limb with the lower part and others with the trunk, so that the least action anywhere is carried through the whole animal. The differential action of the muscles secures to the scapula from which the horse's body hangs, a much longer and swifter throw, a concurrent and auxiliary movement of great muscles, generally supposed to be antagonistic, a grace and harmony that any less perfect system of co-ordination would surely miss. This differential scheme is, perhaps, more apparent in the limbs of the horse than anywhere else, but it extends to other parts of its muscular system and to that of other animals including man.

I think these differential muscles have been a great obstacle to study. One is never sure that he understands the least movement of an animal, unless he can connect it with the whole muscular system, making, in fact, a complete circuit of all the strains. The differential muscles once understood, it is less difficult to connect nearly all the other great muscles with the principal movement of the animal, that of progression in the horse; and to understand, roughly, the combinations necessary for other movements.

On the lines of the mighty and simple strains dominating the movement, and felt intuitively and studied out by him, the master artist groups, with full intention, his muscular forms. No detail contradicts. His men and animals live. Such is the work of three or four modern artists. Such was the work of many an old Greek sculptor.